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1. Introduction

Castellated steel beam is an alternative steel beam usually modified from I-beam and subjected to longitudinal and horizontal cutting through web position. Zirakian and Showkati [1] stated that by using castellated steel beams with hexagonal holes as part of the building structure has several advantages which are (1) increasing moment of inertia, section modulus, stiffness, and bending resistance capacity of beam; (2) optimizing utilization of its original

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beam profile; (3) by creating holes within the body of the beam can be used for installing mechanical and electrical equipment.

Castellated steel beam with hexagonal holes is one of the most popular castellated steel models used in Indonesia. However, there was not enough research in this country related with this type of steel beam. Due to this real condition it is necessary to perform more experimental research or theoretical study for investigating the behavior of castellated steel beam with hexagonal holes. Several investigations related with the behavior of castellated steel beams was performed by Suharjanto [2], Jamadar and Kumbar [3] Jichkar et al. [4]. The behavior investigation results of this type beam are then compared with the behavior of original I-beam. Few researches (Bedi and Pachpor [5], Ellobody [6], Wakchaure and Sagade [7], Wakchaure et al. [8], as well as Priyambodo et al. [9]) were also performed research related with the variations of holes size or height of castellated steel beam. Most of them have investigated about the size of the holes and optimal height of castellated steel beams. So far there was no investigation related with standard of size and holes spacing of castellated steel beams.

This paper explains the results of research for obtaining the optimum size and distance of the hexagonal holes within castellated steel beams. The castellated steel beam models investigated in this study has many variations in opening angle and hexagonal holes distance. The aims of this research are (1) identifying the distribution of stress, deflection and failure of castellated steel beam by conducting finite element method (FEM); (2) finding the optimum size and distance of hexagonal holes within castellated steel beam; and (3) examining the optimum results obtained from FEM analysis by conducting laboratory investigations of castellated steel beam specimens.

Nomenclature

λ	ratio between load and vertical deflection
λ_{IWF150}	ratio between load and vertical deflection in first yield load condition at IWF 150
$\lambda_{kastela}$	ratio between load and vertical deflection in first yield load condition at castellated steel beam
λ_{yield}	ratio between load and vertical deflection in first yield load condition
δv	vertical deflection, in mm
φ	opening angle in hexagonal hole, in degree
$\sigma 1$, $\sigma 2$	principal stress, in MPa
σx, σx	normal stress in x-axis and y-axis, in MPa
σvm	von misses effective stress, in MPa
τxy	shearing stress
b	horizontal projection distance of the hypotenuse of hexagonal hole, in mm
bf	width of flange, in mm
COV	coefficient of variation
db	height of original IWF profile, in mm
dg	height of castellated steel profile, in mm
dt	height of tee section, in mm
e	width of web post, in mm
fy	yield stress of material, in MPa
h	vertical projection distance of the hypotenuse of hexagonal hole, in mm
ho	height of hexagonal hole, in mm
L	span of castellated steel beam
n_{total}	total number of hexagonal holes in castellated steel beam
P	load, in kN
S	strength increased of castellated steel beam to its original profile ($\lambda_{kastela}$ / λ_{IWF150})
tf	thickness of flange, in mm
tw	thickness of web, in mm

2. Research Methods

2.1. General

The method used in this study was divided into two steps. The first step related with the analysis of computer model. The method analysis used in this research was finite element method (FEM) for analyzing castellated steel beam models. The results of analysis are then verified by conducting the second step which are laboratory tested of castellated beam specimens. Figure 1 shows the beam model and loading system used in this researh (two-point loading systems). The parameter of hexagonal holes within castellated steel beam can be seen in Figure 2.

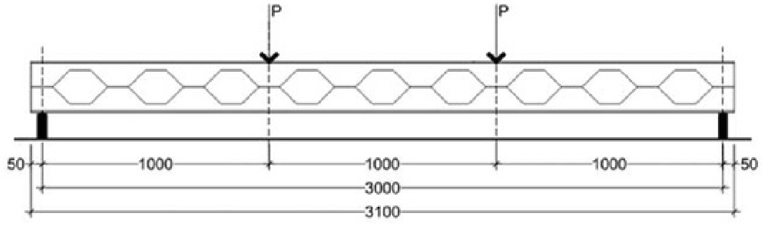


Fig. 1. Two point loading systems in castellated steel beam models

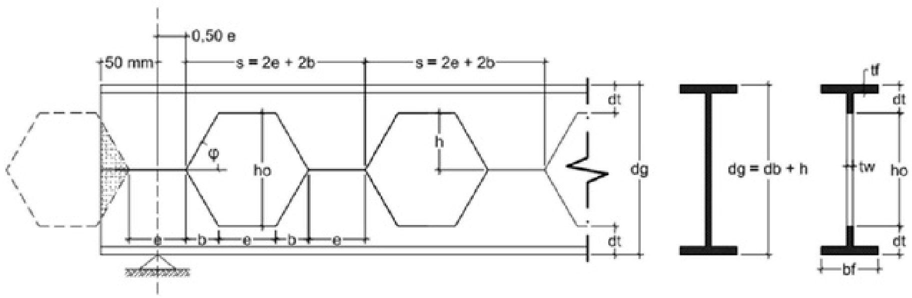


Fig. 2. The parameter of hexagonal hole in castellated steel beam

The standard size of hexagonal holes used in this study was performed using the following information:

- Castellated steel beam size used was 225x75x5x7 mm and modified from original beam profile IWF.150x75x5x7 mm.
- Size (b) is created such that the tilt angle of the hole (φ) is equal to 45°, 50°, 55°, 60°, 65° and 70°. By using these six different angles, size (b) can be calculated as 0.50*ho*; 0.42*ho*; 0.35*ho*; 0.29*ho*; 0.23*ho*; and 0.18*ho* respectively. Finally, size (b) used in this study are 75 mm; 63 mm; 52.5 mm; 43.5 mm; 34.5 mm; and 27 mm.
- Variations in size (e) and total number of holes (n_{total}) within a sample beam was calculated by using the following equation:

$$e = \left(\frac{L - (n_{total}.2.b)}{2.n_{total}} \right) \quad (1)$$

Where (L) is a castellated steel beam span in mm, size (b) and (e) of hexagonal holes can be seen in Figure 2, and (n_{total}) is the total number of hexagonal holes within one sample beam.

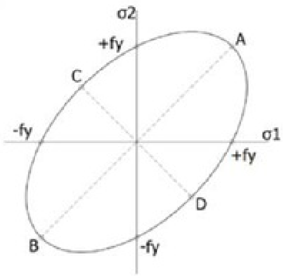
- Total number of specimens used in this research was 60 models. Specimen name, size (b) and (e) and number of holes within one sample (n_{total}) of all models can been seen in Table 1.

Table 1. The dimension of hexagonal hole in castellated steel beam models

Specimen	b (mm)	e (mm)	ntotal	e/ho ratio
IWF.150	-	-	-	-
CB.45-1	75	425.00	3.00	2.833
CB.45-2	75	175.00	6.00	1.167
CB.45-3	75	91.67	9.00	0.611
CB.45-4	75	50.00	12.00	0.333
CB.45-5	75	25.00	15.00	0.167
CB.45-6	75	8.33	18.00	0.056
CB.50-1	63	437.00	3.00	2.913
CB.50-2	63	187.00	6.00	1.247
CB.50-3	63	103.67	9.00	0.691
CB.50-4	63	62.00	12.00	0.413
CB.50-5	63	37.00	15.00	0.247
CB.50-6	63	20.33	18.00	0.136
CB.50-7	63	8.43	21.00	0.056
CB.55-1	52,5	447.50	3.00	2.983
CB.55-2	52,5	197.50	6.00	1.317
CB.55-3	52,5	114.17	9.00	0.761
CB.55-4	52,5	72.50	12.00	0.483
CB.55-5	52,5	47.50	15.00	0.317
CB.55-6	52,5	30.83	18.00	0.206
CB.55-7	52,5	18.93	21.00	0.126
CB.55-8	52,5	10.00	24.00	0.067
CB.60-1	43,5	456.50	3.00	3.043
CB.60-2	43,5	206.50	6.00	1.377
CB.60-3	43,5	123.17	9.00	0.821
CB.60-4	43,5	81.50	12.00	0.543
CB.60-5	43,5	56.50	15.00	0.377
CB.60-6	43,5	39.83	18.00	0.266
CB.60-7	43,5	27.93	21.00	0.186
CB.60-8	43,5	19.00	24.00	0.127
CB.60-9	43,5	12.06	27.00	0.080
CB.60-10	43,5	6.50	30.00	0.043
CB.65-1	34,5	465.50	3.00	3.103
CB.65-2	34,5	215.50	6.00	1.437
CB.65-3	34,5	132.17	9.00	0.881
CB.65-4	34,5	90.50	12.00	0.603
CB.65-5	34,5	65.50	15.00	0.437
CB.65-6	34,5	48.83	18.00	0.326
CB.65-7	34,5	36.93	21.00	0.246
CB.65-8	34,5	28.00	24.00	0.187
CB.65-9	34,5	21.06	27.00	0.140
CB.65-10	34,5	15.50	30.00	0.103
CB.65-11	34,5	10.95	33.00	0.073
CB.65-12	34,5	7.17	36.00	0.048
CB.70-1	27	473.00	3.00	3.153
CB.70-2	27	223.00	6.00	1.487
CB.70-3	27	139.67	9.00	0.931
CB.70-4	27	98.00	12.00	0.653
CB.70-5	27	73.00	15.00	0.487
CB.70-6	27	56.33	18.00	0.376
CB.70-7	27	44.43	21.00	0.296
CB.70-8	27	35.50	24.00	0.237
CB.70-9	27	28.56	27.00	0.190
CB.70-10	27	23.00	30.00	0.153
CB.70-11	27	18.45	33.00	0.123
CB.70-12	27	14.67	36.00	0.098
CB.70-13	27	11.46	39.00	0.076
CB.70-14	27	8.71	42.00	0.058
CB.70-15	27	6.33	45.00	0.042

2.2. Von Mises Failure Criterion

Von Mises failure criterion and also familiar with Maximum Distortion Energy Criterion is used to determine the failure conditions of ductile material. This criterion state that the failure occurs when the maximum value of distortion energy per unit volume within the material exceeds the distortion energy per unit volume required for yield in a tensile-test specimen of the same material [10]. Ilustrative model of Von Mises criterion can be seen in Figure 3. Von Mises failure criterion was bounded by ellipse and can be calculated using equation (2) below:



Boundary conditions:
σ1-axis = +fy and -fy
σ2-axis = +fy and -fy
Point A = +fy
Point B = -fy
Point C = -0,577fy
Point D = +0,577fy
Where, σ1 and σ2 are principal stress, fy is yield stress of material

Fig. 3. Von Mises failure criterion

$$\sigma 1^2 + \sigma 2^2 - \sigma 1.\sigma 2 = \sigma y^2 \quad (2)$$

2.3. Von Mises Effective Stress

Von Mises effective stress is defined as the uniaxial tensile stress that creates the same distortion energy as any actual combination of applied stresses. Failure occurs when the Von Mises effective stress value exceeds the yield stress value of material. The Von Mises effective stress can be calculated using equation (3), where "σvm" is the Von Mises effective stress, "σx" and "σy" are the normal stress in x-axis and y-axis and "τxy" is the shearing stress.

$$\sigma vm = \sqrt{\sigma x^2 + \sigma y^2 - \sigma x.\sigma y + 3\tau xy^2} \quad (3)$$

2.4. Laboratory Testing Setup

In general, the laboratory test was carried out using hinge and roller support system beam and subjected with two-point load systems. The effective length of the beam was 3000 mm. Figure 4 shows the laboratory testing setup.

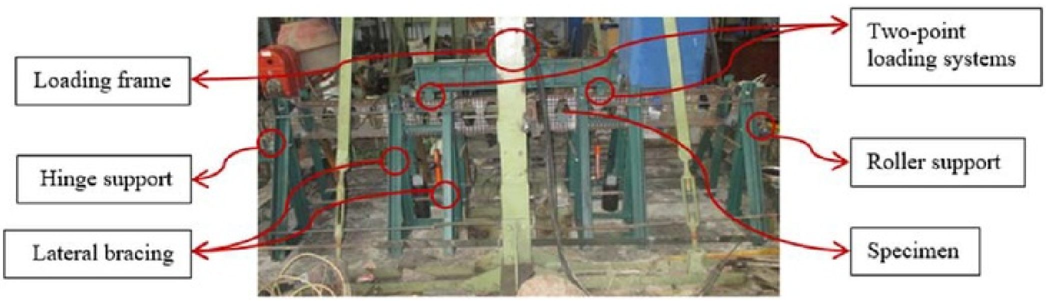


Fig. 4. Laboratory testing setup

3. Results and Discussion

3.1. Strength Increased Analysis of Castellated Steel Beam to Its Original Profile

Based on the FEM analysis results for each castellated steel beam models, the strength increased (S) of castellated steel beam to its original profile can be calculated using equation ($S = \lambda_{kastela} / \lambda_{iwf150}$) and the results can be seen in Table 2. According to Table 2, it can be seen that the optimum conditions, the range of increased strength of castellated steel beams to its original profile, are in between 1.938 to 2.041 times.

Table 2. The increased strength of castellated steel beam to its original profile

Specimens	e/ho ratio	λ_{yield}	Conditions	Strength Increased (S)	Specimens	e/ho ratio	λ_{yield}	Conditions	Strength Increased (S)
IWF-150	-	3,114.50	Controls		CB.60-8	0.127	6,154.58		1.976
					CB.60-9	0.080	6,020.35		1.933
CB.45-1	2.833	2,865.61		0.920	CB.60-10	0.043	5,777.40		1.855
CB.45-2	1.167	5,144.50		1.652					
CB.45-3	0.611	6,005.28		1.928	CB.65-1	3.103	2,508.94		0.806
CB.45-4	0.333	6,304.39	Optimum	2.024	CB.65-2	1.437	4,673.54		1.501
CB.45-5	0.167	6,356.90	Optimum	2.041	CB.65-3	0.881	5,561.32		1.786
CB.45-6	0.056	6,084.34		1.954	CB.65-4	0.603	5,910.77		1.898
					CB.65-5	0.437	6,109.32		1.962
CB.50-1	2.913	2,765.35		0.888	CB.65-6	0.326	6,173.88	Optimum	1.982
CB.50-2	1.247	5,061.88		1.625	CB.65-7	0.246	6,175.44	Optimum	1.983
CB.50-3	0.691	5,883.60		1.889	CB.65-8	0.187	6,114.23		1.963
CB.50-4	0.413	6,239.46		2.003	CB.65-9	0.140	6,039.59		1.939
CB.50-5	0.247	6,334.30	Optimum	2.034	CB.65-10	0.103	5,920.98		1.901
CB.50-6	0.136	6,317.29	Optimum	2.028	CB.65-11	0.073	5,780.34		1.856
CB.50-7	0.056	6,120.30		1.965	CB.65-12	0.048	5,548.19		1.781
CB.55-1	2.983	2,674.45		0.859	CB.70-1	3.153	2,441.26		0.784
CB.55-2	1.317	4,932.65		1.584	CB.70-2	1.487	4,551.59		1.461
CB.55-3	0.761	5,813.01		1.866	CB.70-3	0.931	5,430.49		1.744
CB.55-4	0.483	6,146.88		1.974	CB.70-4	0.653	5,780.49		1.856
CB.55-5	0.317	6,299.08	Optimum	2.023	CB.70-5	0.487	5,991.54		1.924
CB.55-6	0.206	6,304.24	Optimum	2.024	CB.70-6	0.376	6,035.76	Optimum	1.938
CB.55-7	0.126	6,116.11		1.964	CB.70-7	0.296	6,038.45	Optimum	1.939
CB.55-8	0.067	5,910.81		1.898	CB.70-8	0.237	6,014.60		1.931
					CB.70-9	0.190	5,958.27		1.913
CB.60-1	3.043	2,591.80		0.832	CB.70-10	0.153	5,875.75		1.887
CB.60-2	1.377	4,805.67		1.543	CB.70-11	0.123	5,772.74		1.854
CB.60-3	0.821	5,695.42		1.829	CB.70-12	0.098	5,642.77		1.812
CB.60-4	0.543	6,041.09		1.940	CB.70-13	0.076	5,515.92		1.771
CB.60-5	0.377	6,220.23		1.997	CB.70-14	0.058	5,342.77		1.715
CB.60-6	0.266	6,241.45	Optimum	2.004	CB.70-15	0.042	5,030.99		1.615
CB.60-7	0.186	6,233.92	Optimum	2.002					

3.2. Stress Concentration Analysis of Castellated Steel Beam

Based on the optimum conditions obtained for each angle of hexagonal hole the next step was conducting the analysis of stress concentrations for each castellated steel beams models to find out the location of stress concentration. Analysis of stress concentration was performed at the most optimum castellated steel beam models for each angle of hexagonal holes which are CB.45-5, CB.50-5, CB.55-6, CB.60-6, CB.65-7 and CB.70-7 models.

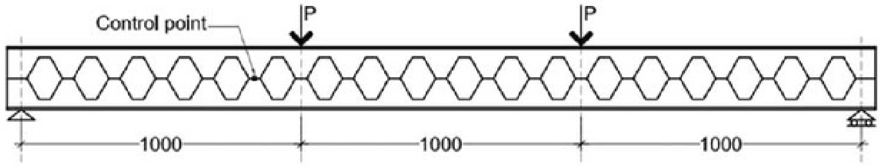


Fig. 5. The location of stress concentration observation for each specimen (control point)

Table 3 illustrates the results of stress concentration analysis for these five models. The stress concentration analysis was observed for each models and located at the first yield point and the centre of weld joint area on web-post as can be seen in Figure 5.

Table 3. The results of stress concentration analysis

Stress components (MPa)	Specimens					
	CB.45-5	CB.50-5	CB.55-6	CB.60-6	CB.65-7	CB.70-7
First Yield Point						
Location	Weld joint area	Hole's corner area	Hole's corner area	Hole's corner area	Hole's corner area	Hole's corner area
σvm	357.973	350.840	350.375	350.936	350.391	350.539
σ1	218.056	379.566	-273.034	-58.654	-272.742	-132.038
σ2	-195.118	67.163	-395.705	-376.567	-395.277	-397.383
Control point						
σvm	356.835	289.155	305.991	245.754	238.712	205.367
σ1	196.729	163.601	174.128	142.878	135.191	117.458
σ2	-215.171	-170.265	-179.187	-140.891	-140.434	-119.675

A summary related with stress concentration analysis results of castellated steel beams are as follows:

- The maximum concentration stress of CB.45-5 model (45° opening angle) is located in the weld joint area of webpost.
- The maximum concentration stress of CB.50-5, CB.55-6, CB.60-6, CB.65-7 and CB.70-7 models are located at the corner area of hexagonal holes.
- The distance of each hole has an influence with the location of maximum stress concentration. The maximum stress concentration was at the corner area of hexagonal holes for wider hole distance holes. While the maximum stress concentration moves to the weld joint area in webpost for shorter hole distance.
- Based on the increased strength analysis to its original profile and the location of stress concentration of all models, 60° angle size with optimum hole distance in between 0.186*ho* to 0.266*ho* are the optimum model of castellated steel beam.

3.3. Comparative Analysis between FEM Analysis Results with Laboratory Testing Results

The optimum FEM analysis results model are then verified using laboratory test. The purpose of this laboratory test is to check correlation between computer model and the real model. Verification was conducted based on maximum deflection and maximum load at the first yield condition of castellated steel beam. The Model used for laboratory test was CB.70-7 model. Comparison between FEM analysis results and laboratory testing results can be seen in Figure 6 and Table 4.

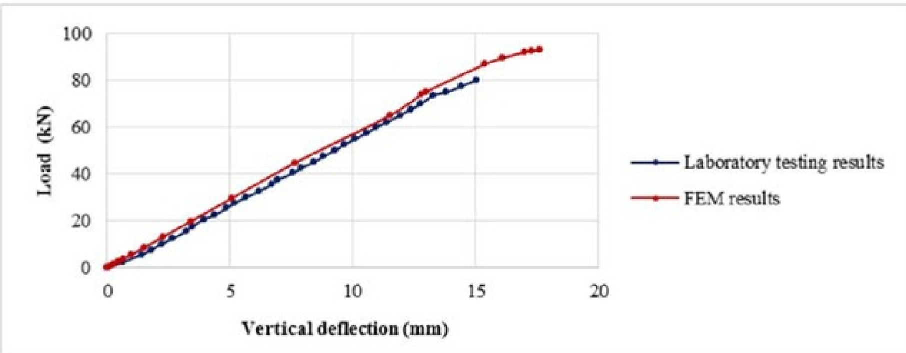


Fig. 6. Comparison between FEM analysis results and laboratory testing results

Table 4. Comparison between FEM analysis results and laboratory testing results

Parameter	First Yield Conditions		Ratio
	FEM Results	Laboratoty Test Results	
(a)	(b)	(c)	(c)/(b)
P (KN)	73.958	75.021	1.014
δv (mm)	12.772	13.790	1.080
P/δv Ratio	5.791	5.440	0.939
		Mean	1.011
		COV	0.069

According to Figure 6 and Table 4, it can be seen that the laboratory testing results has approximately the same results with FEM analysis. The average ratio of "P", "δv" and "P/δv" between both models is 1.011 with COV (coefficient of variation) value 0.069. It can be concluded that the methods used for the analysis of castellated steel beam models with FEM was valid.

4. Conclusion

Based on the analysis of castellated steel beam with FEM and laboratory testing, it can be concluded that:

- The distance of each hole has an influence with the location of maximum stress concentration. The maximum stress concentration was at the corner area of hexagonal holes for wider hole distance holes. While the maximum stress concentration moves to the weld joint area in webpost for shorter hole distance.
- Based on the increased strength analysis to its original profile and the location of stress concentration of all models, 60° angle size with optimum hole distance in between 0.186*ho* to 0.266*ho* are the optimum model of castellated steel beam.
- The laboratory testing results has approximately the same value with FEM analysis results with an average ratio 1.011 and COV (coefficient of variation) value 0.069. The methods used for the analysis of castellated steel beam models with FEM was valid.

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